PRELIMINARY RESULTS ON THE EFFECTS OF DISTRIBUTED ALUMINUM COMBUSTION UPON ACOUSTIC GROWTH RATES IN A RIJKE BURNER

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Abstract

Distributed particle combustion in solid propellant rocket motors may be a significant cause of acoustic combustion instability. A Rijke burner has been developed as a tool to investigate the phenomenon. Previous improvements and characterization of the upright burner lead to the addition of a particle injection flame. The injector flame increases the burner's acoustic driving by about 10% which is proportional to the injector's additional 2 g/min of gas. Frequency remained fairly constant for all test cases.

Preliminary testing shows that the combustion of 17.8 μm or 33.4 μm aluminum powder can triple the acoustic driving in the burner from the "gas only" rate of approximately 135 s^{-1}. The larger aluminum particles, which burn farther into the burner's exhaust, caused a slightly greater acoustic growth rate. Viscous damping appears to limit the effect of distributed particle combustion for particle loadings greater than 8% of the gas flow rate. The information gained in this preliminary study will direct the planned burner characterization and in-depth particle studies.

Background

Solid propellants and liquid propellants are the fundamental source of propulsion to space for current government and private interests. The twin boosters for the shuttle are an obvious example of solid propellant application. Solid propellant rockets offer advantages of high thrust-to-weight ratios, operational simplicity, safety, and low drag due to small frontal area (Oates, 1988).

One drawback to solid propellants is the propensity of the propellant combustion to couple with pressure oscillations in the combustion chamber. This phenomenon is termed acoustic combustion instability. Depending upon the frequency and the amplitude, such oscillations can modify the performance, damage the casing, disrupt the guidance system, or even cause catastrophic failure of the motor.

Combustion instability in solid propellant rockets has been studied intensely for over four decades, but complete understanding remains elusive (Price, 1984). One solution to the stability problem has been the addition of fine metal particles to the propellant matrix to viscously damp acoustic oscillations (Dobbins and Temkin, 1967; Culick, 1974; Derr, 1976; Beckstead, et al., 1984;). Yet consistent success in using particles as acoustic suppressants demands intimate understanding of the interactions between the particles and a motor's acoustic field.

Distributed Combustion

The predominant mechanisms usually considered as driving unstable combustion are pressure and velocity coupling (Price, 1965). A third driving mechanism is distributed combustion where the added metal particles burn far from the propellant surface distributed along the motor's annular cavity (Beckstead, et al., 1985). With propellants that tend to form particle agglomerates or with motors of large mass throughput, distributed combustion may be a significant mechanism contributing to acoustic combustion instability.

Although a burning metal particle and its condensed oxide will viscously damp acoustics, the burning particle will also release energy that can increase or decrease the acoustic field depending on the position of the particle relative to that field. Since particles may burn in a significant portion of a motor's volume, it is likely that some are actually positioned to contribute to the motor's combustion instability. Beckstead (1987) has highlighted a variety of examples from actual motor tests and T-burner experiments which indicate that distributed combustion may be significant, yet this phenomenon has been investigated minimally.

Within the concept of distributed combustion, there appear to be two dominant physical mechanisms. First is the amount of energy released, and the second is the rate of that energy release which is proportional to particle size (Braithwaite, et al., 1984a). A Rijke burner is being developed at Brigham Young University as a tool to clarify the relative importance of distributed combustion and these mechanisms.

Rijke Burner

Rijke (1859) was one of the first to report that a heated wire mesh placed in the bottom half of an open tube would sing as natural convective currents rise. The Rijke burner is a simple extension of the phenomenon with a flame replacing the heated mesh. With the proper geometry, flame, and flow rates, acoustic oscillations will couple with the flame and the convective heat transfer. The reader is directed to papers by Blackshear, 1953; Putnam and Dennis, 1956; Bailey, 1957; Schimmer and Vortmeyer, 1977; and Raun, et al., 1993b for background on the Rijke burner. Diederichsen (1963) found the Rijke burner to be a novel tool in evaluating the effectiveness of particles as damping agents in solid propellants. Finlinson (1987) indicates four reasons for using Rijke burners to study distributed particle combustion over the more conventional T-burner:

1. Distributed combustion is separated from propellant response effects.
2. Premixed combustion of standard fuels (methane, propane, etc.) instead of propellants increases safety, lowers cost, and simplifies experiments.
3. The burner can be operated continuously allowing repeated measurements.
4. Discerning effects of burning with and without particles is straightforward.

Two disadvantages are apparent. First there is the possibility that particle/propellant catalysis is overlooked, or that there is significant particle/gaseous flame catalysis in the Rijke burner. Second, the Rijke burner does not operate at the high temperatures and pressures of propellants so interactions affected by these variables may be missed.

Previous research at Brigham Young University includes: 1) validating the Rijke burner as an experimental tool (Braithwaite, 1984b), 2) developing a computer code to model the phenomenon (Raun, 1986), 3) characterizing the burner at low flow conditions (Finlinson, 1988), 4) examining qualitatively the combustion of several particles (Barron, 1991), and 5) improving the computer code (Brooks, 1991).

The significance of distributed combustion in a Rijke burner is illustrated in Figure 1. Braithwaite (1984b) showed qualitatively that the addition of particles to his Rijke burner could double the acoustic driving over the gas alone case.

Research Progress

The goal of the current research is twofold: first, improve the burner and experimental systems to journey from qualitative to quantitative results, and second, investigate the distributed combustion phenomenon in detail. Past efforts centered on minimizing sources of error and modifying the Rijke burner to operate with a high gas flow rate and elevated flame temperature. Under these conditions a characterization of the upright burner's acoustic growth rate, frequency, and temperature was completed as a function of mass flow rate, gas composition, and geometry (Newbold, et al., 1994).

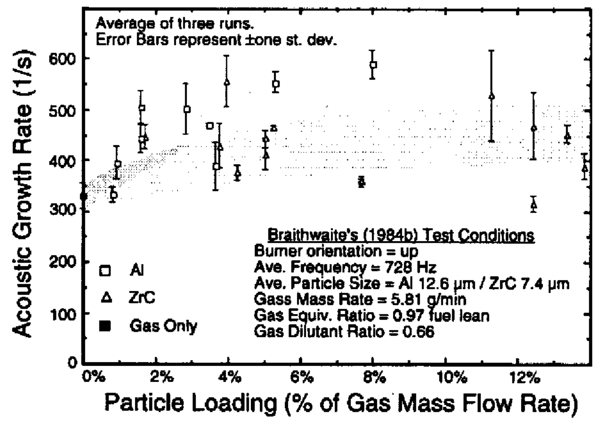

Figure 1. Braithwaite's results (1984b) comparing the acoustic driving of aluminum and zirconium carbide in his Rijke burner.

Particle combustion studies were undertaken, and visibly the aluminum particles appeared to be burning, but microscopic examination showed that only a small portion of the particles were igniting. Considerable effort was exerted attempting to raise the burner's flame temperature so complete ignition might be achieved.

Increasing the flame temperature requires an increase in gas flow rate to avoid flashback. Both a higher flame temperature and higher gas flow rate cause the Rijke burner to excite several frequencies and to exceed the capacity of the acoustic decoupling cone. Unfortunately no solution was found to overcome these problems. Instead a Rijke burner with a welding nozzle flame and injector was proposed and developed.

This new Rijke burner has a relatively cool, flat flame similar to the previous burner. At the center of this flame, a welding nozzle generates a propane/oxygen flame to ignite aluminum particles which have been seeded into the flow. A controlled acoustic field is generated by the Rijke flame, and the small injection flame ignites the particles. The burner was inverted to guarantee that all particles would be entrained.

Recently this new burner was constructed and preliminary tests made. After reviewing the experimental approach, the results of these tests will be shown along with the planned studies.

Experimental Approach

The experimental apparatus and techniques for the current research are the evolutionary result of a decade of research at Brigham Young University. The current experimental approach will be detailed below

Apparatus

Details of the current burner are found in Figure 2. A fiberglass-filled, acoustic decoupling cone is used to start and stop oscillatory combustion. With a butterfly valve open at the entrance to the cold section, acoustics are damped. Closing of the valve starts the growth of oscillations from a zero amplitude. The Rijke flame is near 2400 K and is stabilized on a 20 mesh steel flameholder. The welding nozzle/particle injector produces a propane/oxygen flame at a temperature near 3000 K. Particles are delivered via a syringe feeder. The following burner parameters can be varied: cold length, hot length, gas flow rate, gas composition, and cooling water flow rate. Particle type, size, and loading can also be varied.

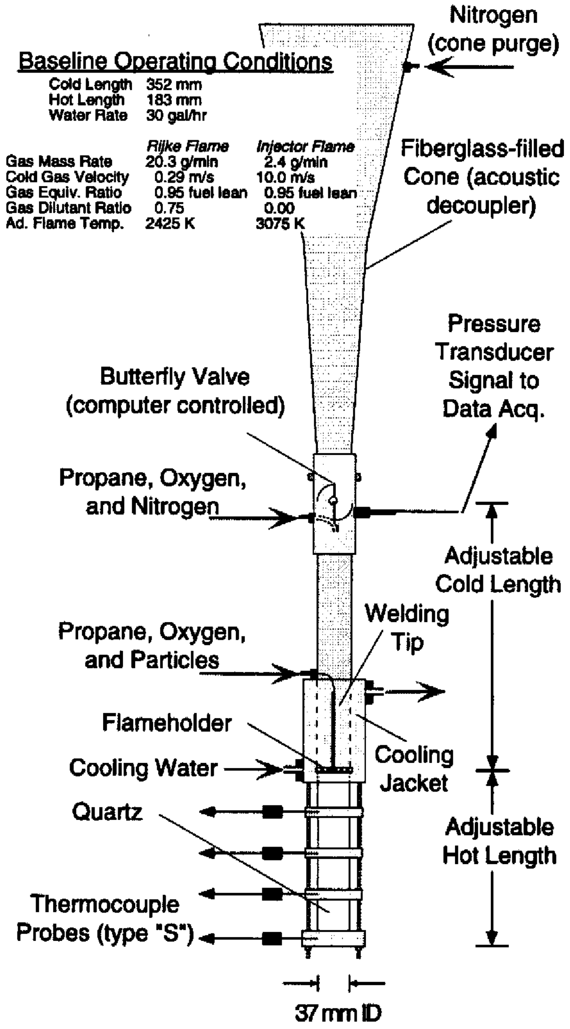

Figure 2. Schematic of the Rijke burner with baseline operating conditions indicated.

Research by Raun (1993a) and Brooks (1991) indicated that a correct temperature profile was crucial to success in modeling the Rijke burner. For this reason, the burner's exhaust was instrumented with exposed junction thermocouples (0.003 inch diameter bare wire, platinum & platinum/10% rhodium) in alumina probes.

To investigate distributed particle combustion, preparations were made to vary the phenomenon in three different ways. First, the distance which a particle will burn can be varied by its reactivity and its size. Aluminum was chosen as a highly reactive particle while zirconium carbide was chosen as a slightly reactive particle. A supply of each particle was secured and then separated into narrow distributions using aerodynamic methods and conventional sieves. The third technique to vary the distributed combustion is simply to increase the mass loading of particles. A syringe feeder was built which can deliver a consistent supply of particles up to 5.0 g/min.

Data Acquisition and Reduction

Acoustic pressure oscillations in the Rijke burner are monitored by a transducer mounted where a pressure antinode develops. After signal conditioning, a data acquisition system digitizes the signal for analysis. Following manual ignition and a 40 min warm-up period, data acquisition is nearly automated from the computer. Data are sampled at 50 KHz for 0.16 sec for a total of 8000 data points. Temperature measurements are also recorded for the exhaust section and the cooling water. Repeated runs are made to average results and estimate data scatter. Figure 3 is a typical pressure signal recorded by the system.

The first 1500 points show the noise from the butterfly valve closing. From 1500 to 3000 the pressure signal grows exponentially until the limiting amplitude begins. The growth of acoustic pressure is the primary parameter of interest and is modeled by the following linear growth equation:

$$P(t) = P_o \, e^{\alpha t} \sin(\omega t + \phi)$$

where

$P(t)$ is the pressure signal as a function of time,
P_o is the initial amplitude of a pressure perturbation,
α is the acoustic growth rate,
t is the time,
ω is the frequency of the signal, and
ϕ is the phase angle.

With the exponential, this equation quickly predicts an unrealistic pressure oscillation; consequently, this equation is only valid for approximately the first half of the signal (Culick, 1974) before nonlinear damping in the system begins to constrain the growth and limiting amplitude is reached.

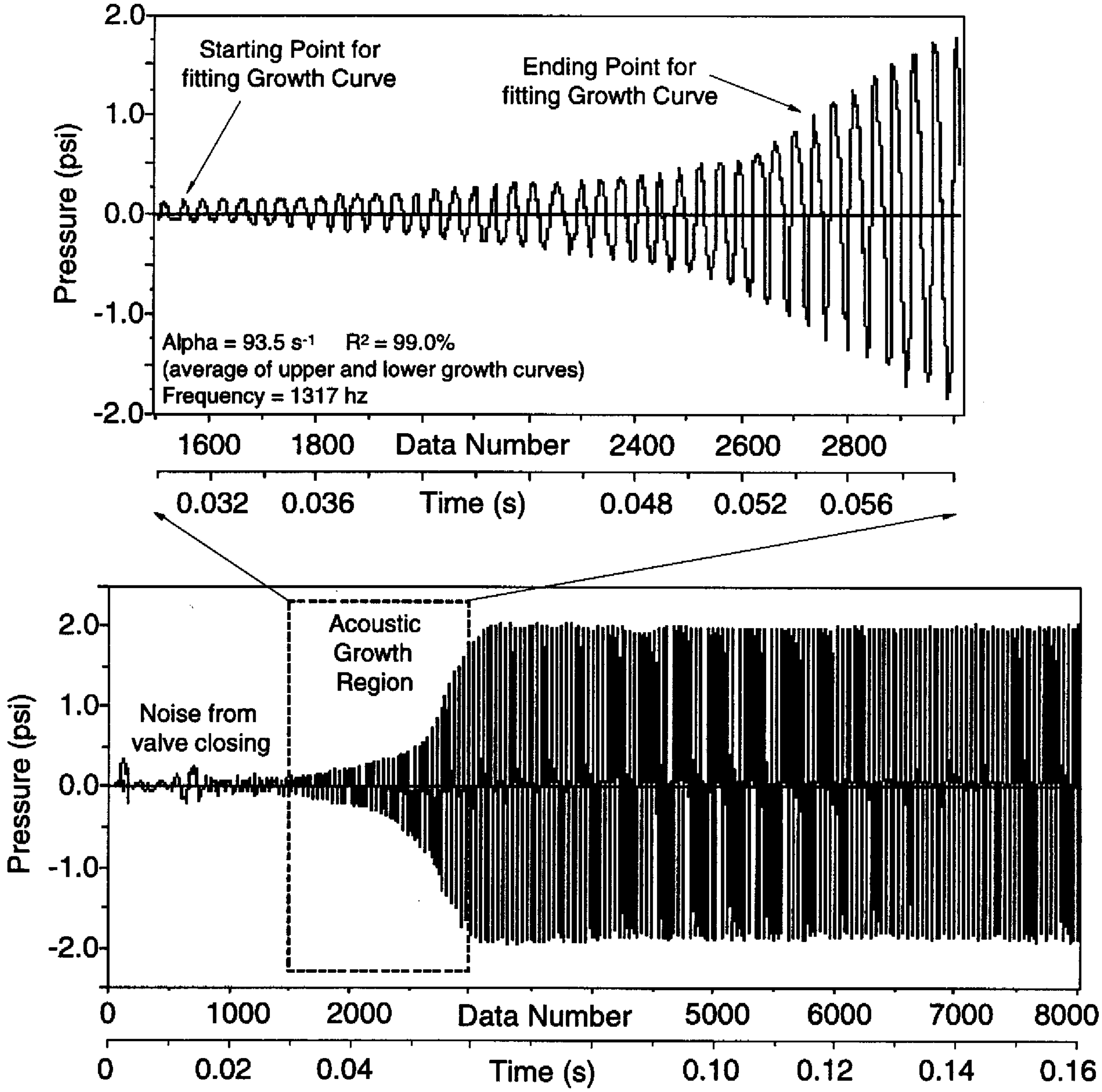

Figure 3. Example pressure signal with the acoustic growth region expanded.

In analyzing each data set, the only subjective action is choosing a starting point. Usually a point is chosen as soon as the transient valve noise dies; thereafter, a computer program reduces the data. The program removes any residual DC offset, performs a Fast Fourier Transform, and calculates the signal's spectral density. After picking pressure peaks, the limiting amplitude is determined and half its value is used as a cutoff point in determining the acoustic growth rate. The logarithm of the pressure peaks for the first half of the growth is a straight line. The slope of the line is the acoustic growth rate and is a measure of the acoustic driving in the system.

This procedure is performed for both the top and bottom sets of peaks and then averaged. The acoustic growth rate usually has a least squares fit (R^2) above 97%. All relevant parameters concerning the growth rate, limiting amplitude, frequency, and temperatures are recorded. For each condition, five to ten runs are made; the standard deviation and average are reported as representative of the operating condition.

<u>Preliminary Results</u>

With the new burner just recently constructed, only preliminary results are available for this paper. The general approach to investigating the distributed combustion phenomenon in the Rijke burner is straightforward. First of all the burner's response without particles must be well understood. A thorough characterization of the upright burner without an injection flame is complete. Now that the burner is inverted and the injector added, a new characterization must be undertaken which includes an examination of the effect of the injection flame itself. These studies will help in interpreting the results of tests with particles combusting in the burner. Also an existing computer model may be used to explain future results.

With the newly revamped burner, only limited data has been taken as shown in Figures 6 and 7. These plots show the effect of particle addition to the Rijke burner. Figure 6 illustrates the results of adding aluminum dust with a mean of 17.8 μm to the Rijke burner, while Figure 7 is for 33.4 μm aluminum. Tests with the third aluminum size, 64.3 μm, were inconclusive since not all of this particle size would ignite. It is hoped that an increase in the Rijke flame temperature might solve this problem.

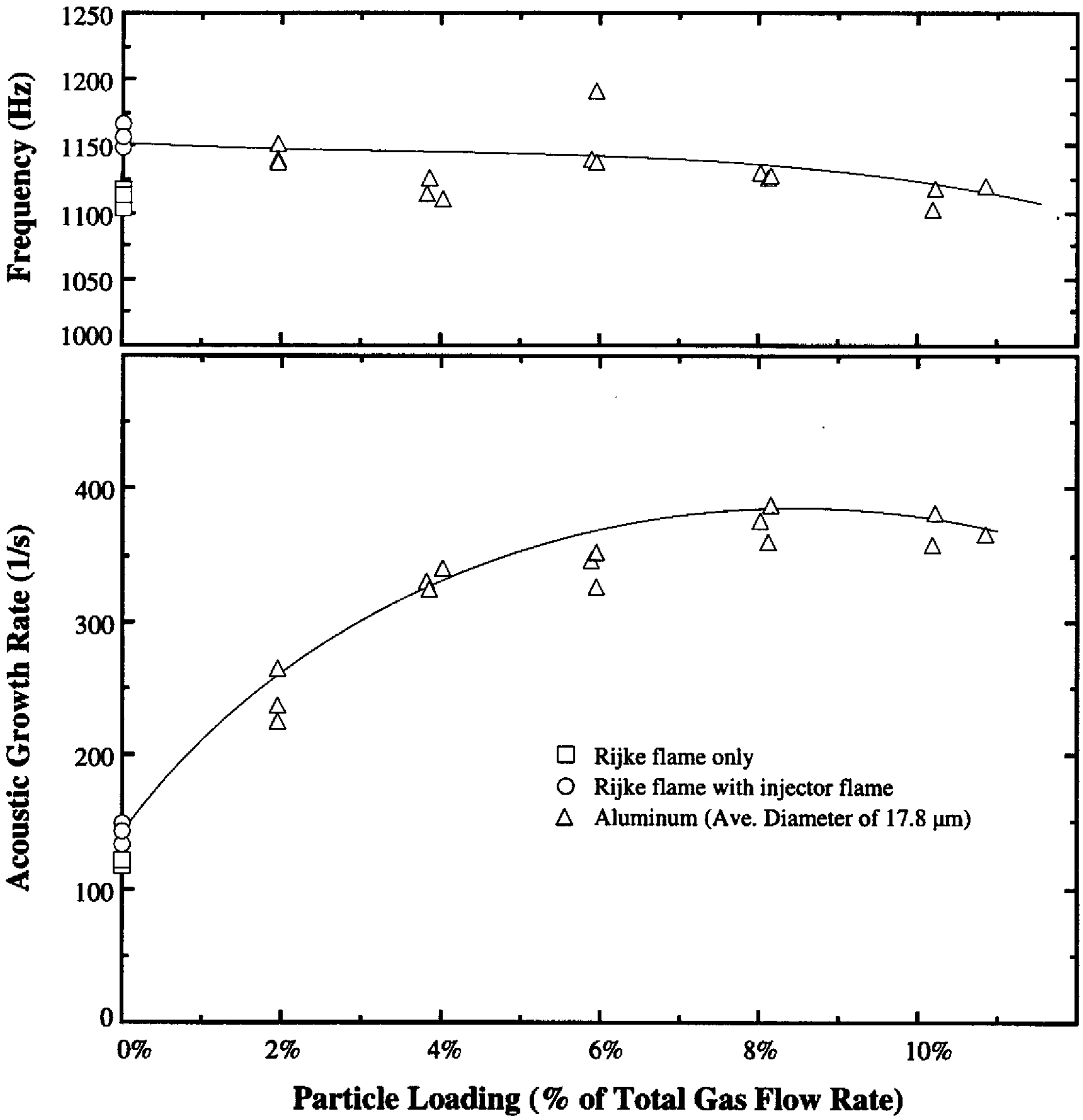

Figure 6. Acoustic growth rate and frequency of the Rijke burner with particle injector as a function of 17.8 μm aluminum particle mass loading.

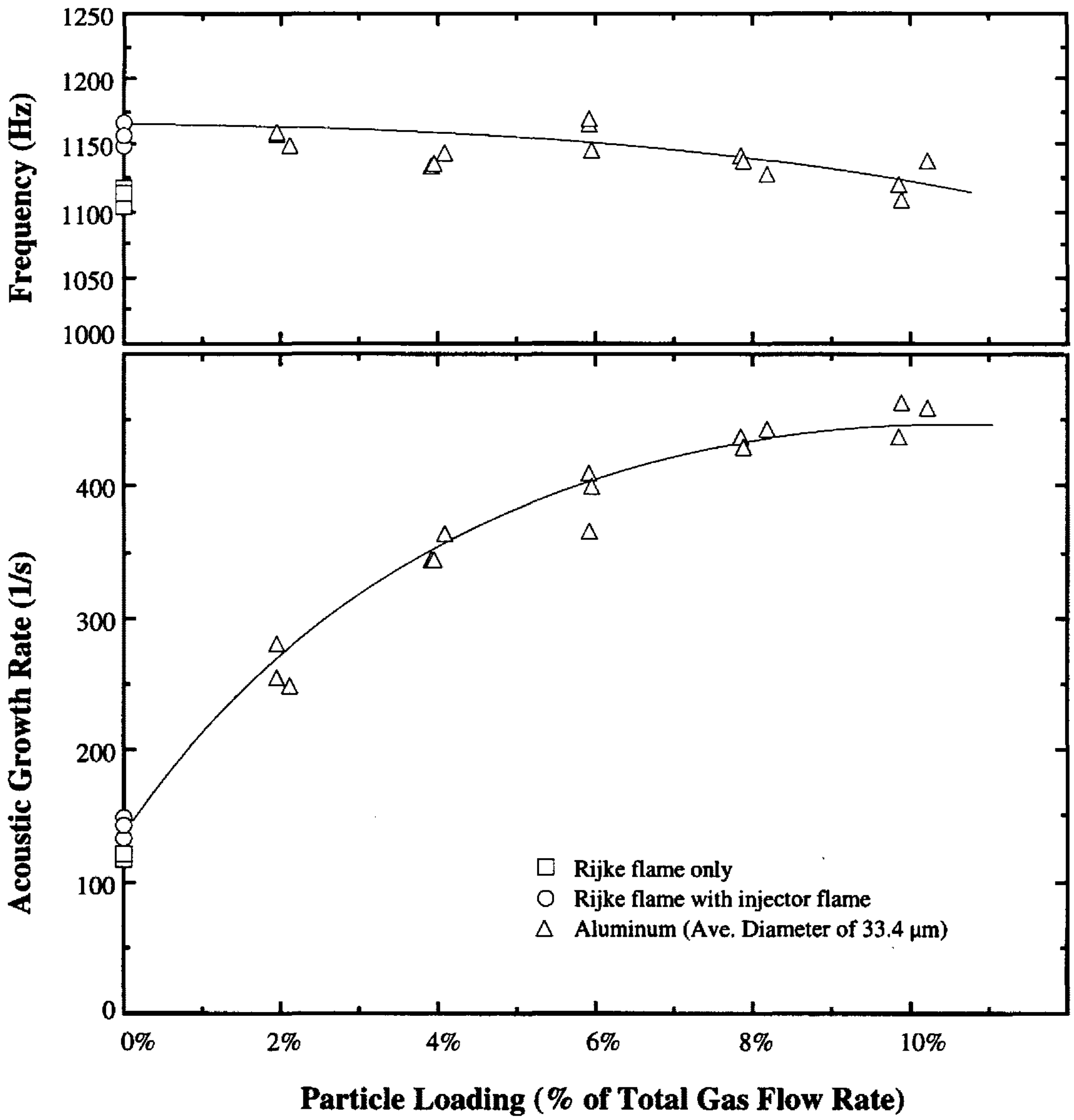

Figure 7. Acoustic growth rate and frequency of the Rijke burner with particle injector as a function of 33.4 μm aluminum particle mass loading.

In the plots of Figure 6 and 7, one can see the two data sets corresponding to no particles in the Rijke burner. The lower data is the burner's response with only a Rijke flame, while the upper data is with the injection flame present also. The increase in acoustic driving and frequency is not unexpected. A previous study using the burner in the upright position (no injector) showed that increasing the gas flow rate could increase the acoustic growth rate. This effect is explained by the simple fact that a greater mass flow rate involves a larger heat release at the flame. The greater heat released in phase with the acoustic field would intensify oscillations. The injector flame extends several inches into the exhaust section and changes the temperature profile significantly. Since the frequency is dependent upon the speed of sound which in turn is dependent upon the local temperature, the change in frequency with the injector flame was anticipated.

The frequency remained fairly constant in both studies when increasing amounts of aluminum was added to the burner. The amount of frequency change from zero to 10% mass loading of aluminum was less than the change observed for the two "no aluminum" cases. It would appear that the general increase in exhaust gas temperature due to the addition of aluminum has a lesser effect on the frequency response than does the distortion caused by the injector flame. It is also apparent that the size of particles added to the burner had little effect on the frequency.

In both figures, one can see that the addition of aluminum increased the acoustic driving in the burner. From the baseline case of no particles, the acoustic growth rate essentially tripled with a 10% mass loading of particles. This is evidence for distributed combustion. As aluminum particles burn along the exhaust portion of the burner, they contribute to acoustic instability in the burner. This effect should be dependent upon the portion of the burner in which the particles combust. It is possible that with a different geometric configuration, the burning particles would decrease the acoustic driving. The new burner with its injector might allow this theory to be explored.

The larger aluminum particles burn farther down the exhaust and tend to increase the acoustic growth rate more than the smaller particles. In both figures, it appears that the effect of adding particles yields diminishing returns as more aluminum is added. This phenomenon might be explained by the competing mechanism of viscous damping becoming more significant with the increased loading of aluminum with its resulting aluminum oxide smoke. The effect of viscous damping should be more pronounced for the smaller aluminum distribution. For a given mass loading, the smaller aluminum will have more particles per cubic centimeter. In Figure 6, one can see that the acoustic driving actually did decrease above 8% mass loading which is consistent with the viscous damping explanation.

Planned Tests

In this preliminary study, only three runs were made at each test condition, but the data scatter was found to be acceptable. Data taken without any particles in the burner established a temporary baseline, but a "gas only " characterization will yet be performed. This characterization should aid in the explanation of particle combustion studies. Also, no temperature data was taken for this preliminary effort. Past experience has shown temperature data to be quite useful and will be gathered in the future. This initial particle combustion data was a check for the completeness of ignition and to obtain a preparatory set of data. After a burner characterization, a large number of particle test conditions are planned as shown in Table 1.

SUMMARY

The viscous damping characteristics of metal particles and their condensed oxides are generally helpful in reducing acoustic combustion instability in solid propellant rocket motors. But the distributed combustion of particles far from the propellant surface may actually contribute to instability. The current work has developed a Rijke burner as a tool to investigate this phenomenon.

Table 1. Tentative test matrix for study of particles in the inverted Rijke burner with injector. Axial wall temperatures, cooling water temperature rise, acoustic growth rate, frequency, and limiting amplitude will be recorded.

Particle (mm)	Mean Particle Size (μm)	Mass Loading (% of Gas Mass Flow Rate)	Total Gas Flow Rate (g/min)	Approximate Frequency (Hz)
Al	17.8	0, 2, 4, 6, 8, 10	22.7	800
Al	17.8	0, 2, 4, 6, 8, 10	22.7	1000
Al	17.8	0, 2, 4, 6, 8, 10	22.7	1200
Al	33.4	0, 2, 4, 6, 8, 10	22.7	800
Al	33.4	0, 2, 4, 6, 8, 10	22.7	1000
Al	33.4	0, 2, 4, 6, 8, 10	22.7	1200
Al	64.3	0, 2, 4, 6, 8, 10	22.7	800
Al	64.3	0, 2, 4, 6, 8, 10	22.7	1000
Al	64.3	0, 2, 4, 6, 8, 10	22.7	1200
ZrC	16.5	0, 2, 4, 6, 8, 10	22.7	1000
ZrC	35.0	0, 2, 4, 6, 8, 10	22.7	1000

Past efforts to improve and understand the upright Rijke burner have led to the installation of a particle injection nozzle and flame. This new burner has been inverted and preliminary tests made. The addition of the injector increases the baseline acoustic growth rate by approximately 10%.

Aluminum particle distributions with means of 17.8 μm and 33.4 μm have been combusted in the burner. With particle addition, acoustic driving approximately triples from the baseline case of 135 s^{-1}. The gains in acoustic driving decrease with increasing mass loading as viscous damping becomes more significant, particularly with the smaller aluminum distribution. A 64.3 μm aluminum distribution did not completely ignite. An increase in the Rijke flame temperature might solve this problem. Frequency remained fairly constant for all test cases.

The addition of an injector to introduce and ignite particles appears to be successful. The information gained in this preliminary study will direct the planned burner characterization and in-depth particle studies.

Acknowledgments

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